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AN LDEF II DUST INSTRUMENT FOR DISCRIMINATION BETWEEN ORBITAL DEBRIS AND NATURAL PARTICLES IN NEAR-EARTH SPACE

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ABSTRACT

We discuss the characteristics of a space dust instrument which would be ideally suited to carry out near-Earth dust measurements on a possible LONG DURATION EXPOSURE FACILITY reflight mission (LDEF II). As a model for the trajectory portion of the instrument we propose for LDEF II, we summarize the characteristics of a SPAce DUSt instrument (SPADUS) currently under development for flight on the USA ARGOS mission to measure the flux, mass, velocity and trajectory of near-Earth dust. Since natural (cosmic) dust and man-made dust particles (orbital debris) have different velocity and trajectory distributions, they are distinguished by means of the SPADUS velocity/trajectory information. The SPADUS measurements will cover the dust mass range ~ 5×10^{-12} g (2 μm diameter) to ~ 1×10^{-5} g (200 μm diameter), with an expected mean error in particle trajectory of ~ 7° (isotropic flux). Arrays of capture cell devices positioned behind the trajectory instrumentation would provide for Earth-based chemical and isotopic analysis of captured dust. The SPADUS measurement principles, characteristics, its role in the ARGOS mission, and its application to an LDEF II mission are summarized.

INTRODUCTION

In near-Earth space, it is well known that both orbital debris and natural particles contribute to the particulate environment (refs. 1-6). For some time, it has been recognized that the orbital debris component represents a serious and growing hazard to future space operations, both from the point of view of catastrophic collision, as well as erosive damage to critical surfaces (sensors, optics) resulting from long-term exposure to the smaller orbital debris particles (refs. 2,4). For cosmic dust particles, it has been shown that the only means of determining their sources (comets, asteroids, interstellar) is by *in-situ* velocity/trajectory measurements (ref. 1). Similarly, for near-Earth dust particles, velocity/trajectory measurements would provide the ability to discriminate between debris and natural particles (ref. 7). However, because of the limited exposure of velocity/trajectory sensors to near-Earth space up to the present time, the spatial distribution, mass spectrum, trajectory, and time variations of the small particle component (< 1 cm diameter) of orbital debris have not been well determined (refs. 2,4).

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The first LONG DURATION EXPOSURE FACILITY (LDEF I) (refs. 5,6) has demonstrated the value of the LDEF concept for an overall survey of the near-Earth space radiation environment. In particular, the 5.8 year space exposure of LDEF I has yielded a wealth of impact feature data from near-Earth particulates (orbital debris and cosmic dust) having a wide range of dimensions and impact velocity (refs. 5,6).

Although LDEF I did not carry a dust instrument which could have provided direct measurements of particle mass, velocity, and trajectory, the Interplanetary Dust Experiment (IDE) aboard LDEF I demonstrated that debris particles appear to dominate the particulate environment at LDEF I altitude and that a large fraction of the debris particles are encountered as transient particle clouds (ref. 8). However, at the present time, quantitative classification of LDEF impact particle types and their sources is just beginning to emerge (ref. 9). The present-day lack of quantitative measurements of the flux, velocity/trajectory, and time characteristics of small debris particles continues to hamper development of reliable evolutionary modeling for orbital debris (ref. 4), and the need for these data remains as an important goal in this field.

A second LDEF mission (LDEF II) carrying the dust instrument we describe here would directly address this need, as well as provide important information on a) the orbital characteristics and possible sources of near-Earth cosmic dust and b) the flux and mass distribution of meteor-stream particles which may be encountered by LDEF II.

PROPOSED LDEF II DUST INSTRUMENT

The main design objective of the particle velocity/trajectory instrumentation which has been under development by the University of Chicago group has been the capability to measure individual particle trajectories with sufficient accuracy to permit identification of their parent bodies. This, combined with chemical and isotopic analysis of the captured material in a capture cell device (and/or returned sensors), permits a direct study of the physical, chemical and isotopic composition of matter from a known parent body.

This objective and ongoing developments have led to the basic concept behind the dust instrumentation we propose for an LDEF II mission, which is illustrated schematically in Figure 1. The main components are: a) a dust trajectory system, consisting of two identical planar arrays (D1 and D2) of polyvinylidene fluoride (PVDF) dust sensors, and b) a capture cell system, consisting of an array of capture cell devices placed behind the D2 array.

The trajectory system would provide measurements of impacting particle flux, mass, velocity (by time-of-flight) and trajectory. The capture cell system would provide for capture of particle residues following penetration of the trajectory system by the impactor. Subsequent Earth-based analyses would yield chemical and isotopic composition of the residues. Thus, the combined trajectory-capture cell instrumentation provides the capability to measure the orbital elements of individual particles prior to capture. Although unambiguous identification of a specific source body will probably not be possible for most of the impacts, identification of generic classes (i.e., comet, asteroid, interstellar, orbital debris) will be possible, with the corresponding particle chemical and isotopic composition determined by analysis of the captured residue. In what follows, we describe some of the characteristics of these two systems.

LDEF II Dust Trajectory System

As a model for the dust trajectory system for LDEF II, we describe the characteristics of a SPAce DUSt (SPADUS) instrument currently under development for launch on the Advanced Research and

Global Observation Satellite (ARGOS) in 1995. This instrument will be jointly developed by groups at The University of Chicago (dust sensors and linear electronics), the Lockheed Space Sciences Laboratory (digital electronics), and the Space Sciences Division of the Naval Research Laboratory (mechanical design and construction). SPADUS will be integrated and flown by the DOD Space Test Program, with funding for The University of Chicago portion of SPADUS development provided by the Office of Naval Research and NASA. A schematic of the SPADUS instrument is shown in Figure 2.

SPADUS Sensors

Each of the two sensor arrays (D1 and D2 in Figure 2) contains 16 PVDF copolymer dust sensors. The theory, characteristics, and development of the PVDF and PVDF copolymer dust sensors developed at The University of Chicago have been discussed in detail in earlier reports (refs. 10-12). Briefly, a PVDF (or PVDF copolymer) sensor, shown schematically in Figure 3a, consists of a thin film of permanently polarized material. A hypervelocity dust particle impacting the sensor produces rapid irreversible local depolarization in the sensor volume destroyed (penetration hole), which results in a large and fast (ns range) current pulse at the input to the electronics. The output pulse amplitude, in general, depends on impacting particle mass and velocity (refs. 10-12) and is sharp in time, as illustrated in Figure 3b. We note that this fast output pulse permits a high counting rate capability for the sensor (up to 10^4 impacts s^{-1} with no corrections, and up to 10^5 impacts s^{-1} with known corrections).

The highly successful performance of the University of Chicago PVDF-based instruments (Dust Counter and Mass Analyzer - DUCMA) (ref. 11) throughout the VEGA 1/2 missions to comet Halley proved the high space reliability of PVDF sensors and their value for space dust studies (refs. 13,14). Continuing studies of PVDF sensors and electronics led to a) instrumentation for particle velocity determination using thin sensors in a time-of-flight arrangement (ref. 15), which is the basic concept behind the SPADUS trajectory system, and b) development of the PVDF copolymer dust sensor (ref. 12), which is expected to have advantages over pure PVDF sensors, and which will be used for the SPADUS trajectory sensors. In Table 1, we summarize the characteristics of PVDF sensors.

SPADUS Particle Velocity Determination

Particle velocity may be determined by a time-of-flight (TOF) arrangement (ref. 15), as illustrated in Figure 4, and the particle velocity determining characteristics of two PVDF copolymer sensors in this TOF arrangement are illustrated in Figures 5 and 6. Our calibrations (ref. 12) show that for impactors having diameter $D_p > 10$ μm and impact velocity < ~ 10 km/s, SPADUS will determine impact velocity by TOF with an accuracy ~ 1-4%. For impact velocities > 10 km/s, particle vaporization, ablation, and fragmentation become important, and velocity information may be lost for a significant fraction of all impactors having $D_p < \sim 40$ μm. For $D_p > \sim 40$ μm, we anticipate that > 50% of all impactors will provide TOF data with an expected error in velocity measurement of ~ 20-30%, this larger error resulting from the relatively large impactor velocity loss upon D1 penetration (ref. 12).

SPADUS Particle Trajectory Determination

With regard to particle trajectory measurement, it had been suggested that a ~ 1° trajectory error might be required in order to distinguish particles of cometary origin from particles of asteroidal origin (ref. 1). However, it is not clear that this degree of trajectory accuracy is warranted, since it has been shown that particles from these two sources have different distributions of trajectories (ref. 7). Consequently, although the University of Chicago group has developed two-dimensional position-sensing PVDF sensors (x,y sensors) which yield particle impact coordinates with typical errors of ~ 1-3 mm for x and y (trajectory error of ~ 1° for two x,y sensors separated by ~ 20 cm) (refs. 15,16), our SPADUS design has been chosen to provide a trajectory accuracy of the order of 5° by using arrays of non-position-sensing PVDF sensors.

This is illustrated in Figure 7, which shows the computed distribution of error angle θ, which is the angle between the computed trajectory (i.e., the detector centers) and any allowed trajectory involving the D1 and D2 detectors (ref. 15). The data plotted show that approximately one-half of all computed trajectories will be in error by less than ~ 7°, which should permit discrimination between classes of trajectory (i.e., comets *vs* asteroids).

SPADUS Data

For each SPADUS dust impact, 65 Kbits of data are generated which include a) impact time on D1 (1 s accuracy), b) TOF between D1 and D2 (0.25 μs resolution), c) D1, D2 wave forms (2000 points, 0.25 μs per point, 8-bit pulse-height-analysis (PHA) per point) for each of four records, d) identification of the D1 and D2 sensors impacted, and e) PHA over 32 mass intervals, for each of the 32 dust sensors. These data, when analyzed in terms of the different velocity/trajectory distributions for cosmic and debris dust particles (mean of ~ 20 km/s for cosmic dust, and ~ 13 km/s for orbital debris), are expected to permit discrimination between these two particle classes for a substantial fraction of all analyzed events. Further, the time-velocity-trajectory capabilities of SPADUS will permit identification of possible transient debris clouds, as well as meteor stream encounters.

SPADUS Electronics

A simplified block diagram of the SPADUS electronics is shown in Figure 8. The primary electronics for each dust sensor consists of an amplifier chain, a discriminator, a 16-channel PHA, and a timing register. Amplified and shaped D1 signals which exceed the discriminator threshold start the PHA, TOF, and transfer the current clock count to the timing register. From the D1 to D2 TOF and electronic identification of the D1,D2 sensors impacted, particle velocity and trajectory are determined. Summed signals from the 16 sensors of each sensor plane are generated and analyzed by 8-bit flash analog-to-digital converters running at 4 MHz (2000 time points) and an additional 16-channel PHA is recorded. Particle mass is determined from the amplitude of the signal measured by the PHAs and the particle velocity (refs. 10-12).

Recording of the D1,D2 wave shapes not only provides redundant TOF data and redundant high resolution PHA measurements, but also permits identification of possible multiple fragments impacting D2, as well as possible spurious sensor signals resulting from acoustic backgrounds (refs. 10,11). Instrument commanding provides for deletion of any of the sensors from the electronic chains and various threshold and gain changes. Dual computers provide redundancy, collect, format, and store all dust data (16 Mbits storage), operate the in-flight calibration system, and perform all spacecraft interface functions. Custom rad-hard gate arrays, containing both analog and digital sections, are used throughout the electronics. The main characteristics of the SPADUS instrument are summarized in Table 2.

LDEF II Capture Cell System

The capture cell system we would propose for LDEF II would consist of stacked thin foils and/or aerogels (ref. 17). The results which have already been obtained for combined PVDF trajectory-capture cell systems (stacked foils) have established that, for ~ 75% of the impactors with velocities < ~ 8 km/s, thin PVDF trajectory systems satisfy the requirements of a) velocity/trajectory determination, b) of identification of the location of particle fragments in capture cells, and c) of sufficient fragment mass following penetration of the trajectory sensors for successful capture and subsequent chemical and isotopic analysis (refs. 12,17).

SPADUS ROLE IN THE ARGOS MISSION AND APPLICATIONS TO LDEF II

The ARGOS objective is to demonstrate advanced attitude and position determination, electric propulsion, and conduct upper atmosphere imaging and environment studies, with SPADUS providing measurements of the particulate environment. Figure 9 summarizes the characteristics of the spacecraft, mission, and experiments. SPADUS dust data to be obtained on the ARGOS mission (833 km altitude) during the time frame ~ 1995-1998 would be ideally complemented by corresponding data which could be obtained by a SPADUS-type instrument (with capture cells) carried by an LDEF II spacecraft at lower altitude over the same time interval. These combined data would provide important information regarding the altitude/inclination dependence of near-Earth orbital debris fluxes, as well as provide an important data base to aid in reliable evolutionary modeling for orbital debris.

Of special interest for both ARGOS and an LDEF II would be an energetic nucleon (electrons, ions, neutrals) telescope, which could be mounted within the SPADUS digital electronics box, for continuous monitoring of the ARGOS and LDEF II nucleon environments, and the addition of this telescope (Lockheed group) is currently planned for SPADUS.

The prime purpose of the energetic nucleon telescope is to obtain nucleon flux data which would a) be of diagnostic value in resolving possible ambiguities in the low event-rate SPADUS dust data, and b) provide information of importance to the other experiments aboard ARGOS and LDEF II, since it is well known that x-ray, UV, and optical systems can be upset by solar proton events, as well as trapped radiation-belt particles. Its secondary purpose is to obtain an *in-situ* map of the radiation-belt nucleon environment and obtain new science on the angular and energy distributions of precipitating electrons and ions. Although final design of the telescope is not yet complete, it will consist of an ion/neutral telescope (ref. 18) and an electron telescope located within the SPADUS digital electronics box.

SPADUS REQUIREMENTS

Mounting and Orientation

To maximize the impact rate, SPADUS requires that the normal to the trajectory sensors be pointed along the spacecraft velocity vector (~ 1° accuracy), as illustrated in Figure 2.

The SPADUS electronics will contain an instrument clock (activated by SPADUS Power On and continuously running with 1 s resolution). For each impact, the SPADUS clock records the impact time (1 s accuracy), and particle velocity/trajectory data with respect to the SPADUS trajectory system axes is stored in SPADUS memory. To determine the particle orbital parameters from these data, SPADUS requires a) a spacecraft time signal (1 s accuracy) to correlate a SPADUS particle impact time with a unique spacecraft time, and b) access to a continuous record (~ 1 s resolution) of spacecraft position, velocity and attitude.

Electrical Connections

Electrical connections are required between the SPADUS instrument and the spacecraft for operating power, commands, and telemetry. Unregulated 28 V dc voltage from the spacecraft would be acceptable, with all voltage conversion and regulation being carried out within the SPADUS electronics. Estimated SPADUS power required is 6.5 W continuous.

Telemetry and Commands

SPADUS requires active spacecraft data transmission to ground stations at an average bit rate of ~ 4 bits/s. Upon Power On, SPADUS operates in NORMAL MODE and continuously accumulates dust particle data. Occasionally (~ once per month), SPADUS is put into CALIBRATE MODE (either by ground command or automatically) which provides an electronic calibration of the instrument. Additional commands (threshold changes, etc.) might be used occasionally, but only under special circumstances (CONTINGENCY).

CONCLUSIONS

We have described the characteristics of a combined trajectory-capture cell dust instrument for a possible LDEF II which would provide quantitative measurements of particle flux, mass, velocity and trajectory, as well as permit capture of particle residue for Earth-based chemical and isotopic residue analysis. The velocity/trajectory capability of the instrument would distinguish orbital debris from natural dust and provide important information on the orbital characteristics and possible sources of the natural component.

Data from this instrument on LDEF II, when combined with corresponding data from an identical instrument (without capture cells) to be carried on the ARGOS near-Earth satellite, would provide important *in-situ* information regarding the altitude/inclination dependence of near-Earth orbital debris fluxes, as well as provide a new data base to aid in modeling of orbital debris generation and evolution.

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Table 1. Characteristics of Polyvinylidene Fluoride (PVDF) Dust Detectors

- Require no operating bias voltage.
- Long term stability during storage. Operate indefinitely -50°C to +100°C with no degradation in dust response.
- Recent development of PVDF copolymer sensors expected to extend stability range to -60°C to +115°C.
- Highly radiation resistant. No measurable change in response up to $\approx 10^7$ rad.
- Response to dust impacts unaffected by high background fluxes of charged particles.
- Fast detector response (few ns) enables accurate counting for high dust fluxes (intense transient dust streams, planetary rings).
- Proven space performance on VEGA-1/2 missions to comet Halley.

Table 2. Characteristics of the SPADUS Instrument*

DUST PARTICLES

Single sensor:	36 cm^2, 6 μm thick PVDF copolymer.
Particle mass (10 km/s):	$5x10^{-12}$ g ($D_p = 2$ μm) to $1x10^{-5}$ g ($D_p = 200$ μm).
Particle velocity:	1 to 10 km/s with 1 to 4% error. Greater error for velocity > 10 km/s.
Particle trajectory:	mean angular error of 7° for isotropic dust flux.
Sensitive area of D1 array (16 sensors):	0.058 m^2.
Geometry factor for isotropic dust flux:	a) D1 array -- 0.18 m^2 sr. b) D1,D2 arrays -- 0.04 m^2 sr.
Field of view (full cone):	a) 180° for flux. b) 120° for trajectory.
Low resolution Pulse-Height-Analysis:	32 channels for each of 32 dust sensors.
High resolution Pulse-Height-Analysis:	2000 time points, 8-bits/point, each of 4 channels.
Expected impact rate:	a) ~ 2/day to 20/day (flux). b) ~ 0.2/day to 2/day (trajectory).

PHYSICAL

a) Estimated total power: 6.5 W. Estimated total weight: 18 pounds.
b) thermal: operating temperature range -40°C to +50°C for dust sensors and electronics.
c) mounting: dust sensor normals along spacecraft velocity vector.
d) data readout: readout at an average bit rate of ~ 4 bits/s.
e) commands: CALIBRATE and CONTINGENCY commands occasionally.
f) attitude: spacecraft attitude (~ 1° accuracy) and velocity (~ 1% accuracy) required.

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* The addition of an energetic nucleon telescope to SPADUS would provide measurements of electrons (20 keV to 2.5 MeV) and ions (20 keV to 20 MeV) and would add ~ 3 pounds and ~ 3.5 Watts to the SPADUS weight and power values listed above.

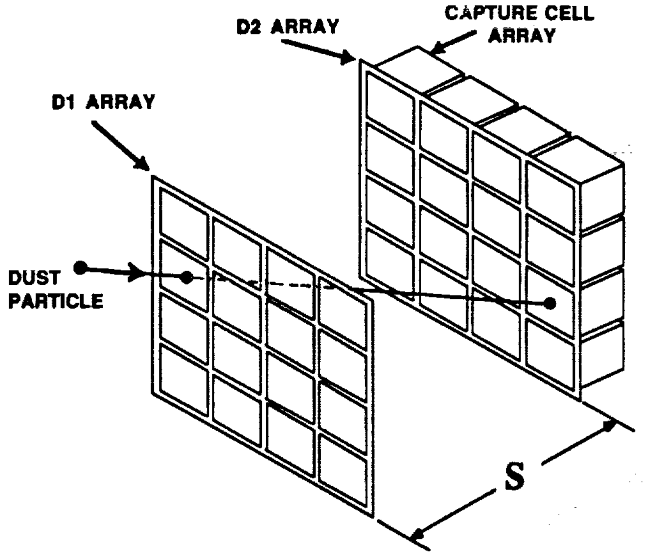


Figure 1. Schematic illustration of the dust instrumentation proposed for LDEF II, consisting of a trajectory system (D1 and D2 PVDF sensor arrays with separation *S*), and a capture cell system (an array of capture cell devices positioned behind the D2 sensors).

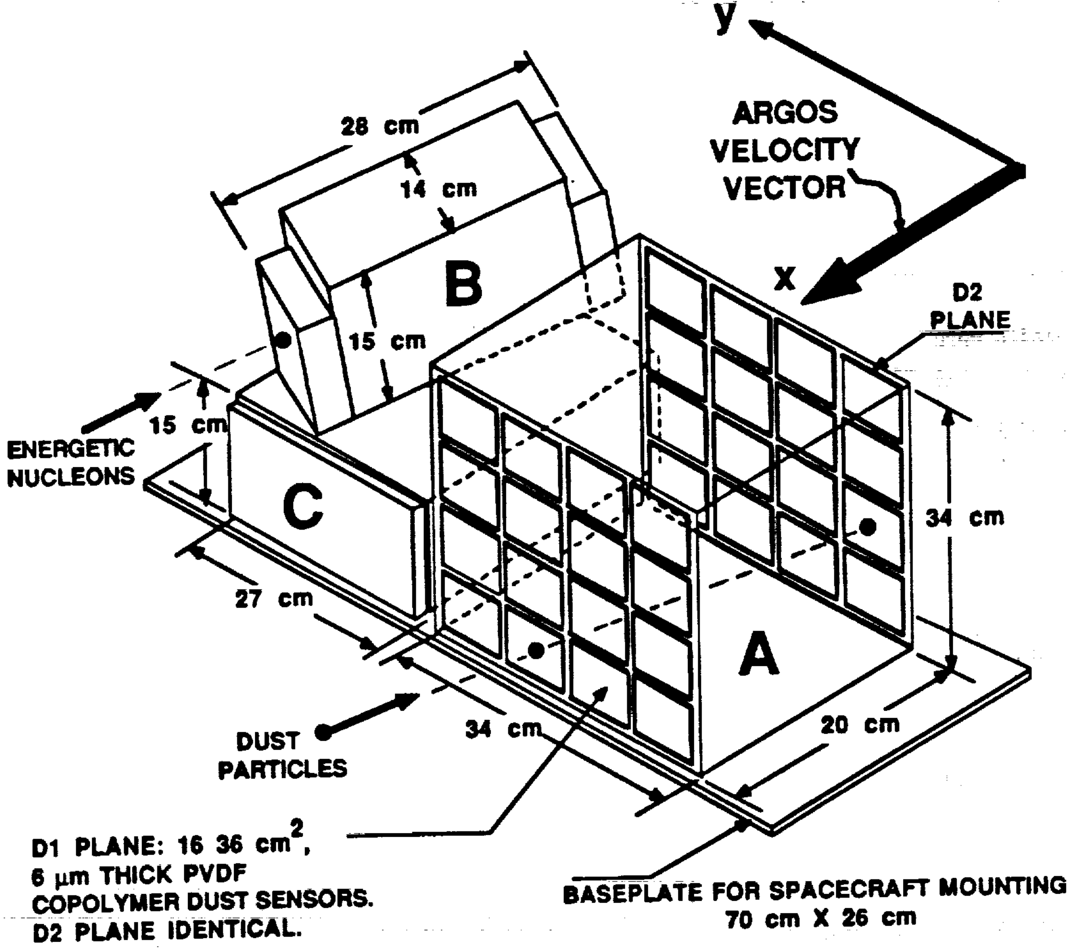


Figure 2. Schematic of the SPADUS instrument showing the dust trajectory system (A), the digital electronics box containing an energetic nucleon telescope (B), and the linear electronics box (C).

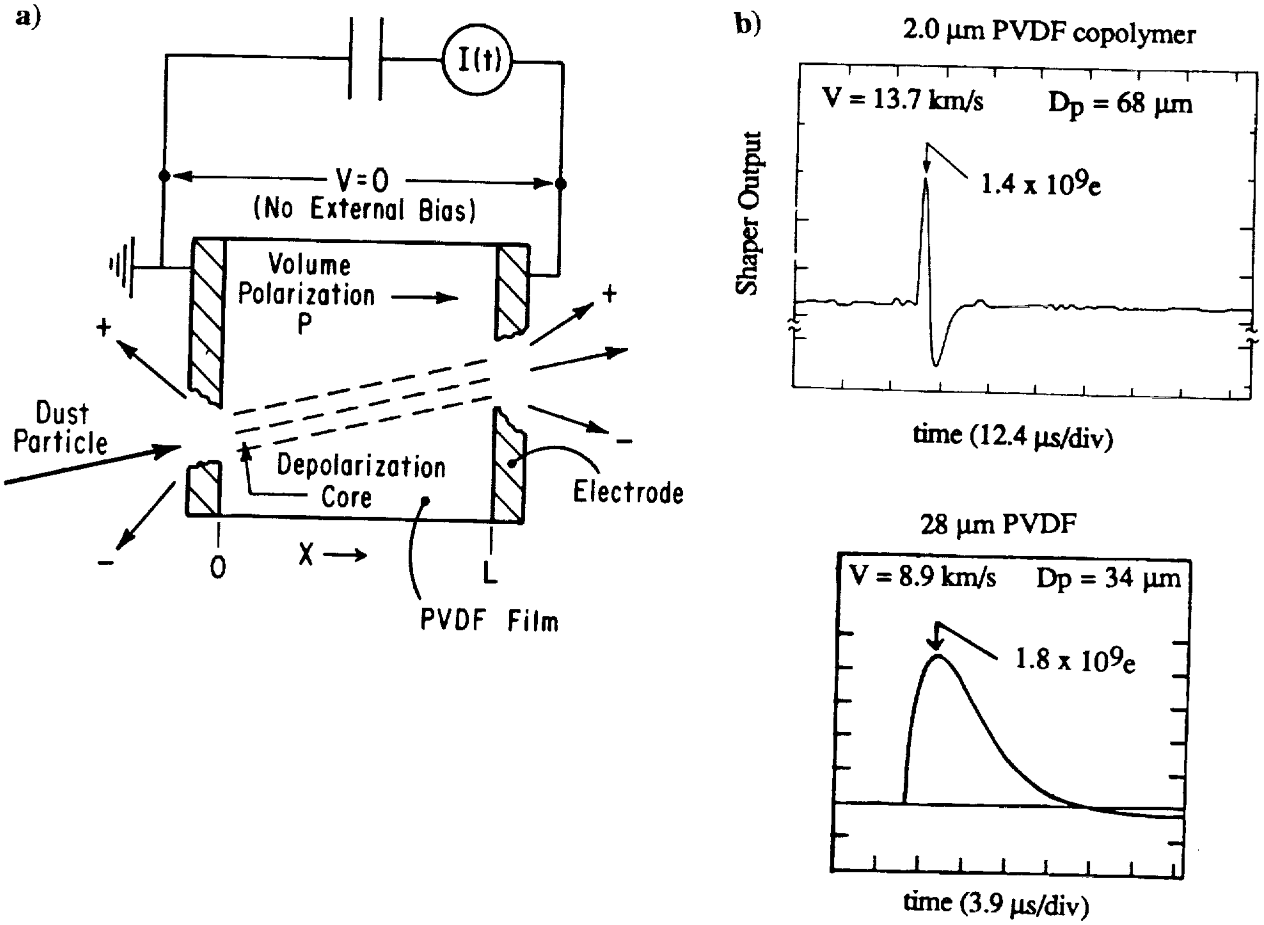


Figure 3. a) Schematic drawing of a polarized polyvinylidene fluoride (PVDF) dust sensor. The sensor film, of thickness L, has a built-in volume polarization P, as shown. b) Examples of output pulses from PVDF sensors resulting from glass impactors having impact velocity V and diameter D_p. The signal amplitudes in units of number of electron charges are indicated.

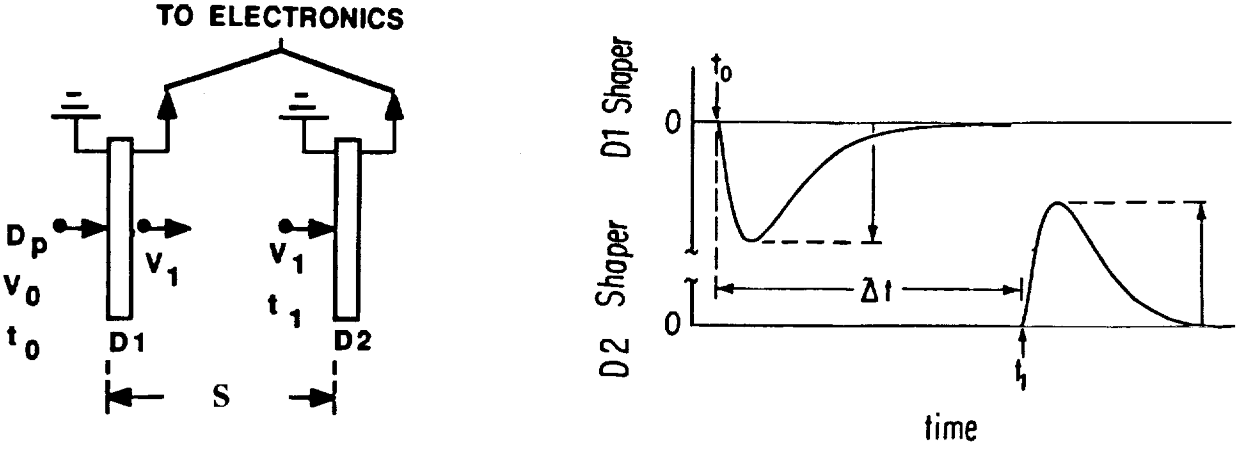


Figure 4. Illustration of particle impact velocity determination by time-of-flight. An impactor with velocity V_0 and diameter D_p impacts a thin PVDF D1 sensor at time t_0, emerges from D1 with reduced velocity V_1 and impacts D2 at a later time t_1, with $\Delta t = t_1 - t_0$. With S known and Δt measured, $V_1 = S/\Delta t$. From the amplitude of the D1 output pulse and V_1, both V_0 and D_p are determined from calibration data.

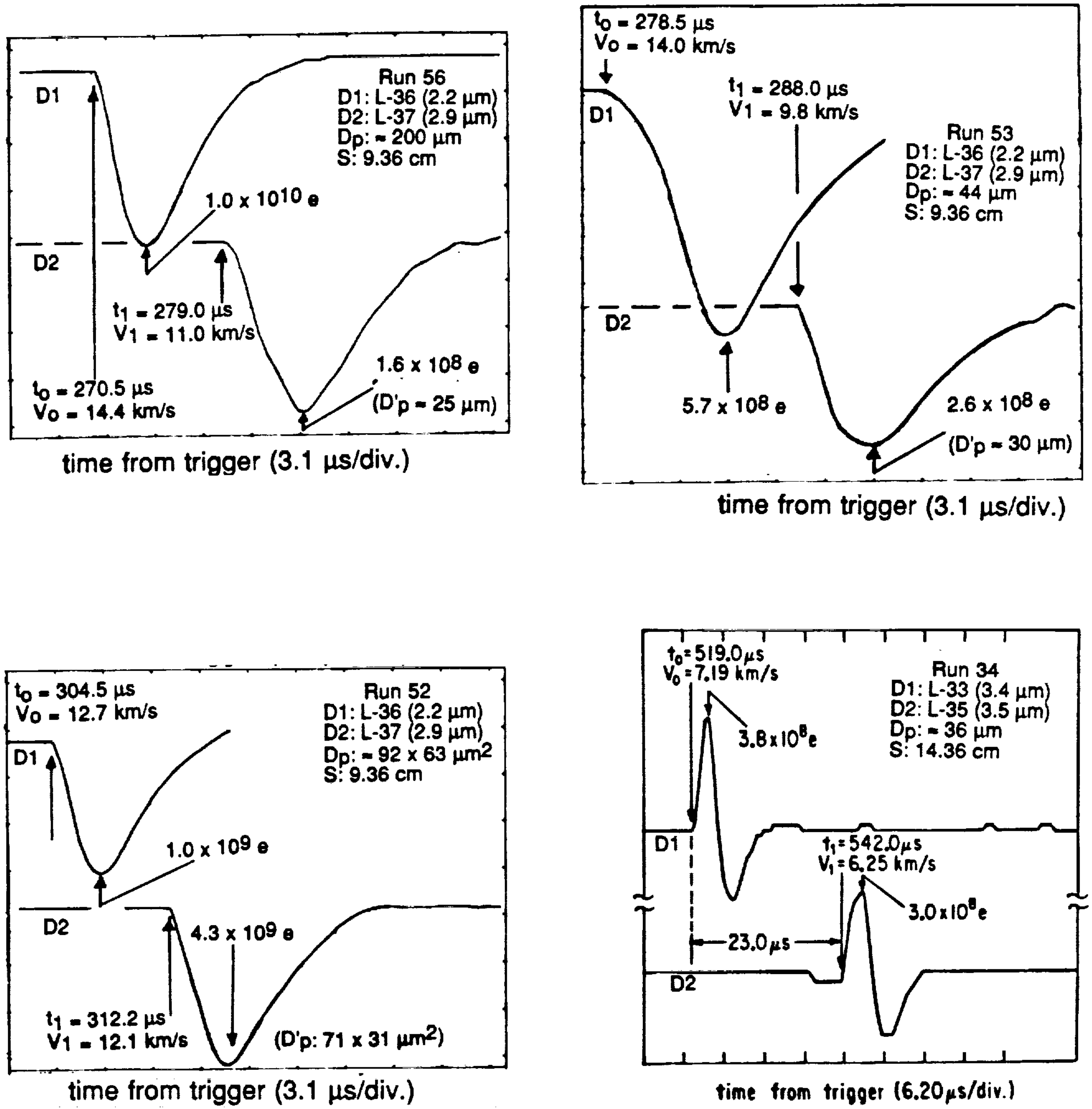


Figure 5. Examples of TOF data obtained during dust calibrations carried out at the Munich (Germany) dust accelerator facility. Indicated are the D1,D2 sensor thicknesses, impactor diameter D_p, and D1,D2 separation S.

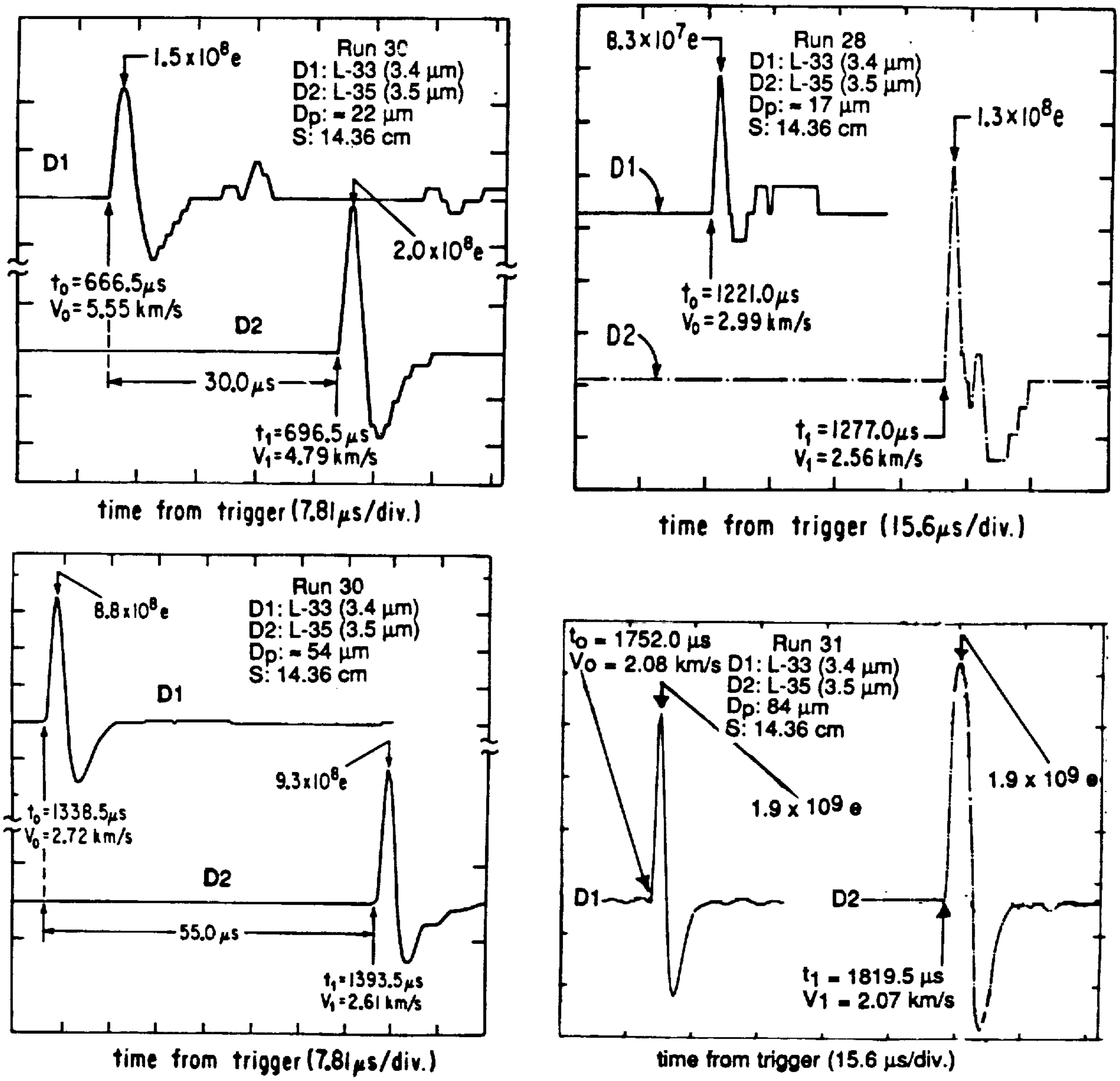


Figure 6. Examples of TOF data obtained during dust calibrations carried out at the Munich (Germany) dust accelerator facility. Indicated are the D1,D2 sensor thicknesses, impactor diameter D_p, and D1,D2 separation S.

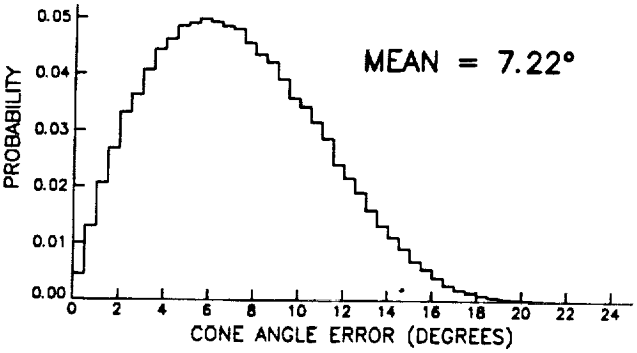
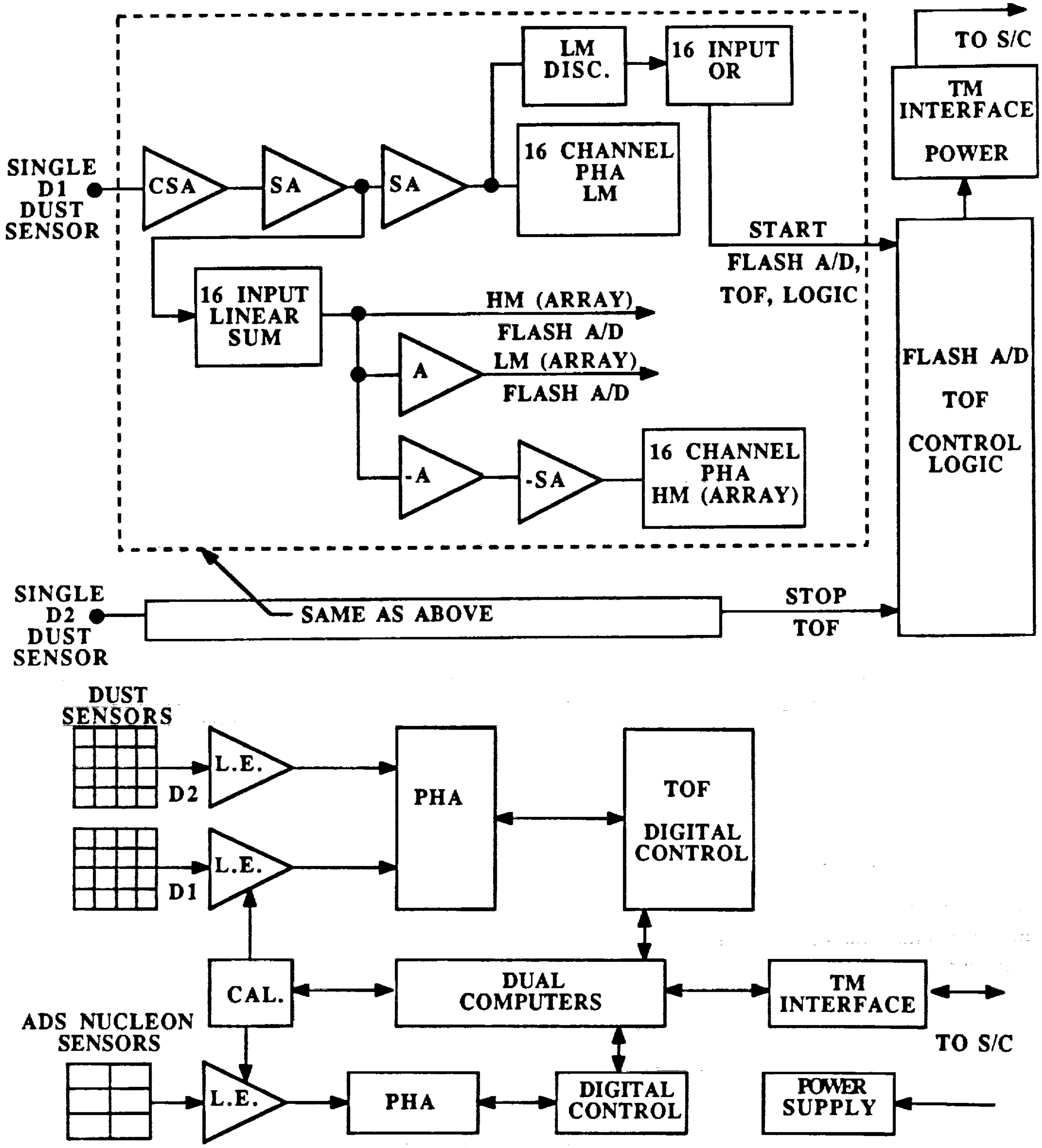


Figure 7. Distribution of error angle θ for an isotropic dust flux obtained from a Monte Carlo run for the SPADUS trajectory system shown in Figure 2.



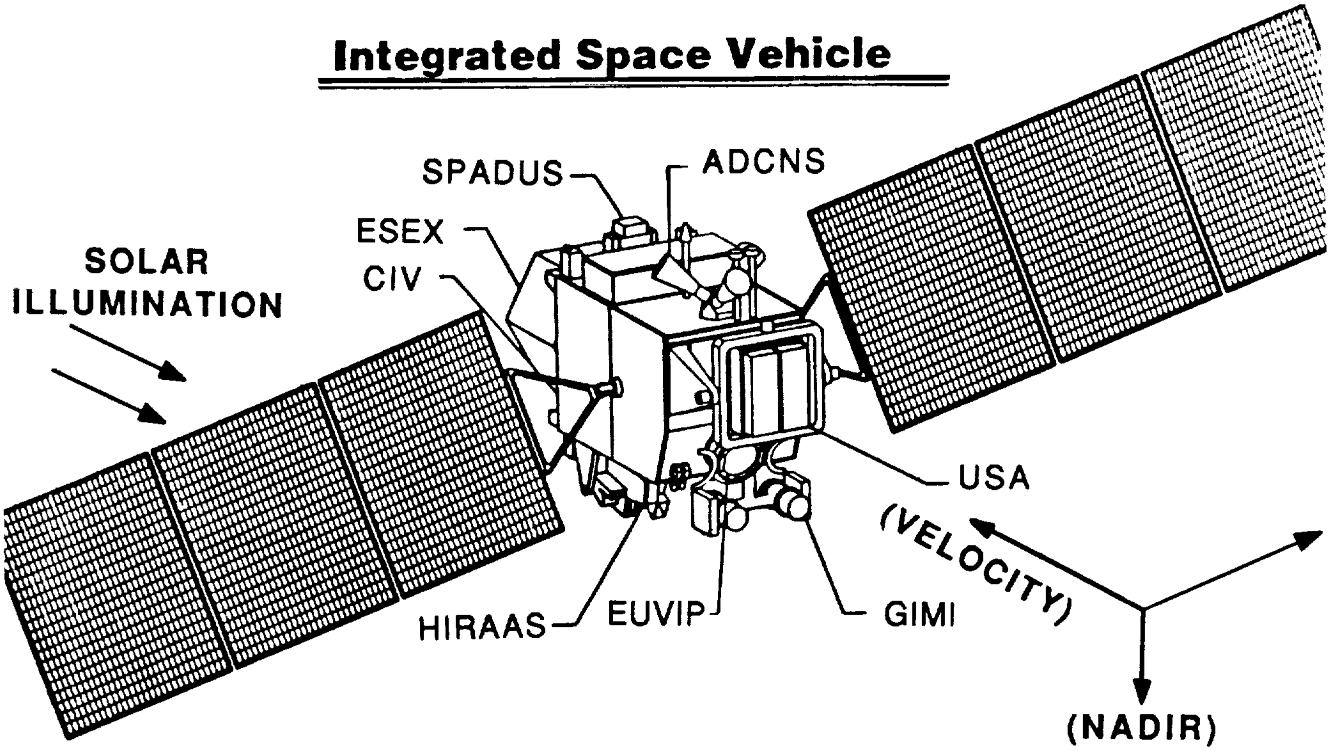
NOTE: TOF - Time-Of-Flight; TM - Telemetry; PHA - Pulse Height Analysis; ADS - Ancillary Diagnostic Sensor; L.E. - Linear Electronics; CAL. - Calibrate; LM - Low Mass; HM - High Mass; A/D - Analog to Digital; SA - Shaping Amplifier

Figure 8. Simplified schematic of SPADUS electronics.

ARGOS

(ADVANCED RESEARCH AND GLOBAL OBSERVATION SATELLITE)

Integrated Space Vehicle



ARGOS EXPERIMENTS

1. EUVIP	ARMY	UV Imager
2. HIRAAS	NRL	UV Spectroradiometer
3. USA	NRL	Unconv. Stellar (X-Ray)
4. GIMI	NRL	UV Camera
5. CIV	Phillips	Critical Ionization Velocity
6. ESEX	Phillips	Arcjet Propulsion Engine
7. ADCNS	DARPA	Attitude Determination Control & Navigation System
8. SPADUS	ONR	Space Dust Experiment

ARGOS MISSION CHARACTERISTICS

a) ORBIT: Circular near polar (98.7°), 833 km altitude (sun synchronous).
b) MISSION DURATION: 3 years.
c) STABILIZATION: 3 - axis stabilized
d) LAUNCH VEHICLE: Delta II
e) EXPERIMENTS: Total of 8
f) FLIGHT INSTRUMENT DELIVERY: September 1994.
g) LAUNCH: September 1995.

Figure 9. Integrated ARGOS space vehicle, mission characteristics, and experiments.